

# **The elemental abundances in the intracluster medium as observed with *XMM-Newton***

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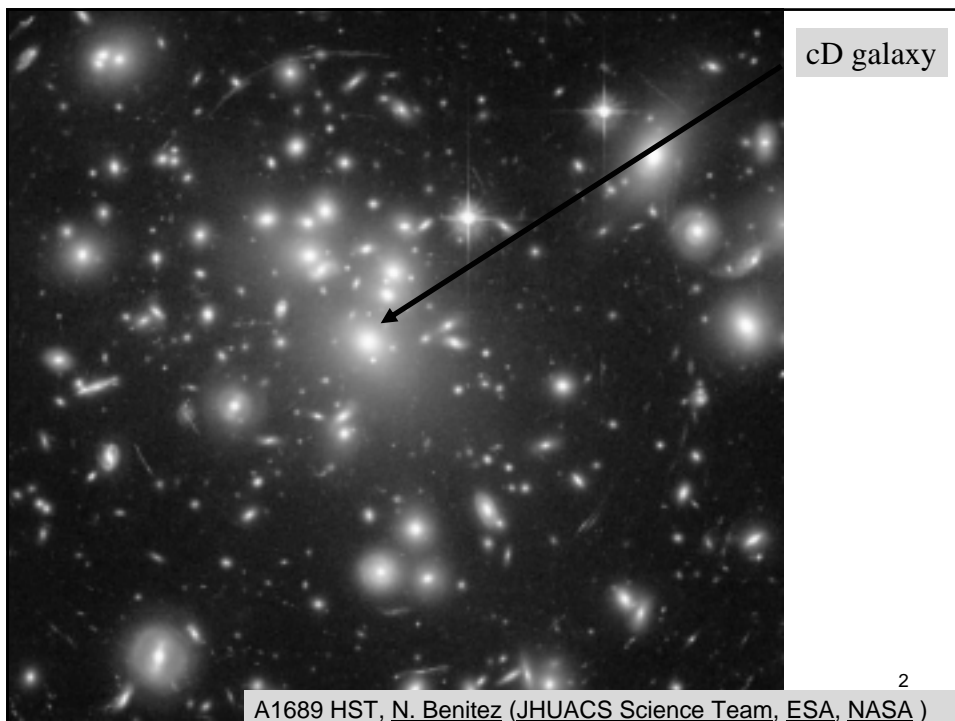
1. Introduction  
galaxy cluster, ICM, abundance ratios, supernovae  
Ia/II
2. XMM observations and analysis of 19 clusters
3. Results
4. Discussion and Future Prospects

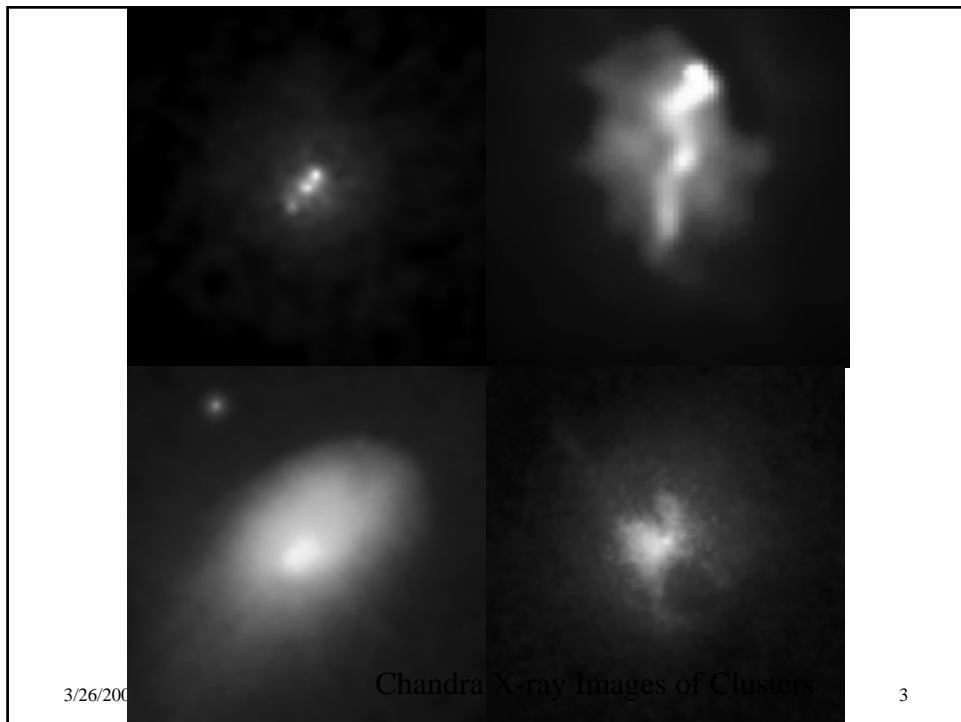
Collaborated with J.S. Kaastra, J. W. den Herder,  
J. A. M. Bleeker (SRON), J. R. Peterson (Stanford)

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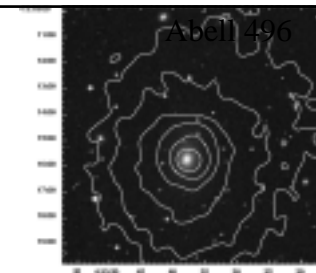
## Galaxy Cluster

### Star

- ◆ 100-1000 of galaxies

### Hot Plasma (Intra-Cluster Medium)

- ◆  $n_e = 10^{-4} - 10^{-2} \text{ cm}^{-3}$
- ◆  $T_e = 10^7 - 10^8 \text{ K}$
- ◆  $L = 100 \text{ kpc} - 1 \text{ Mpc}$
- ◆ *More massive than stellar mass.*
- ◆ Metal rich



### Dark Matter

- ◆ Kinetic energies of galaxies and plasma, Gravitational lenses indicate large mass.
- ◆ More than 10 times massive than stars and plasma

Largest system bounded by the dark matter potential

# Ionized Fe lines from clusters

## The ICM contains a large amount of metal.

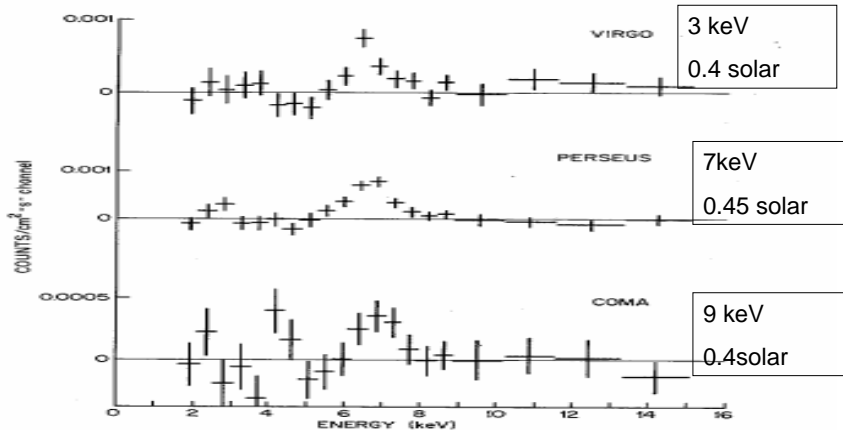


FIG. 2.—Residual counts for Virgo, Perseus, and Coma, obtained by subtracting from the data the best-fit thermal continua from Table 1.

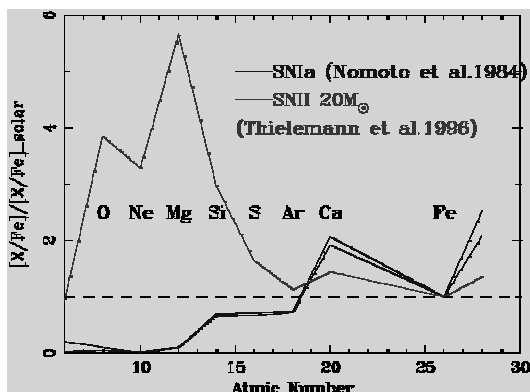
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Serlemitsos et al. 1977

# Metal productions in supernovae

## SN Ia + II



\* Still large uncertainty in SN II model.

SN Ia

3-8 Msun White dwarf.

N.S. driven by gas accretion from the companion.

Ex. SN 1006

SN II

Massive stars (> 10 Msun)  
Gravitational collapse

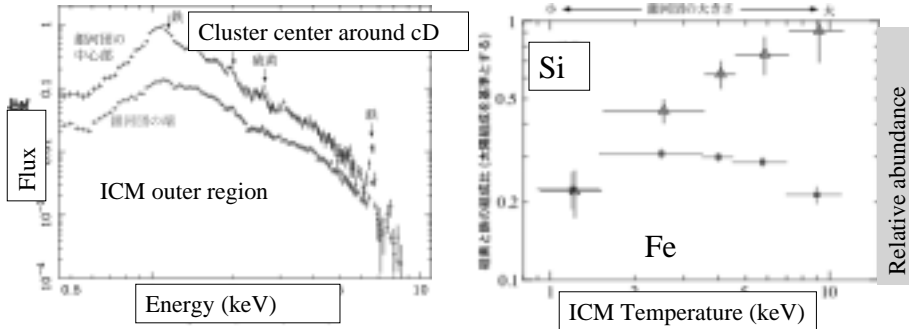
Ex. ) Cas-A

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## Previous Results



- ◆ Spatially resolved X-ray spectroscopy (BBXRT, ASCA, SAX)  
-> Si, S, Fe distributions.
- ◆ An excess of Fe around cD galaxy (e.g. Fukazawa et al. 2000; De Grandi and Molendi 2001)
- ◆ Variations of the Si/Fe ratio with a cluster (e.g. Finoguenov et al. 2000) and *among clusters* (Fukazawa et al. 1998).

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## Limitations before XMM/Chandra

Spatial and spectral resolution of previous instruments are limited.



1. The derived total amount of metals to depend on their assumed spatial distribution.
2. a systematic uncertainty in the temperature structure. (particularly important in the central cool regions). severe errors in the abundances of Fe and other elements.
3. In most cases these measurements are limited to the Fe, Si and S abundances (Not O).

# XMM-Newton (1999-)

- ◆ EPIC (CCD; PN+MOS)
  - ❖ Larger effective area in 0.3-10 keV.
  - ❖ Better spatial resolution (15" in PSF HPD).
  - ❖ Better spectroscopic capability in low X-ray energy band.
  - ❖ (*high background*)
- ◆ RGS (Reflection Grating Spectrometer)
  - ❖ High resolution spectroscopy in 0.3-2 keV (O and Fe-L resolved spectrum)
  - ❖ Only for peaked X-ray core of clusters.

## XMM Observations

	z	T(ICM; keV)		z	T(ICM; keV)
NGC 533	.018	1.3	A 496	.032	4.4
A 262	.016	2.2	A 3112 *	.077	4.5
Ser 159 *	.057	2.4	A 1795 *	.064	5.8
MKW 9	.040	2.6	A 399	.071	6.2
2A 0335	.034	3.0	Perseus	.018	6.5
A 2052 *	.036	3.1	A 1835	.254	7.2
Hyd-A	.055	3.4	Coma *	.024	7.5
MKW 3s	.046	3.5	A 754	.056	8.0
*			A 3226	.061	8.7
A 4059	.047	4.0			
A 1837	.071	4.4			

Cool, med-T, hot clusters

Soft excess (<0.5 keV) clusters (\*)

# EPIC Spectral Analysis

## Spectral Extraction

- ◆ Remove high background periods.
- ◆ Remove the bright X-ray sources.
- ◆ Corrections for the PSF and vignetting.
- ◆ Concentric spectra of 0-0.5-1-2-3-4-6-9-12 arcmin. in radius (spherical symmetry)
- Deprojection of spectra (Kaastra et al. 2004 in detail)

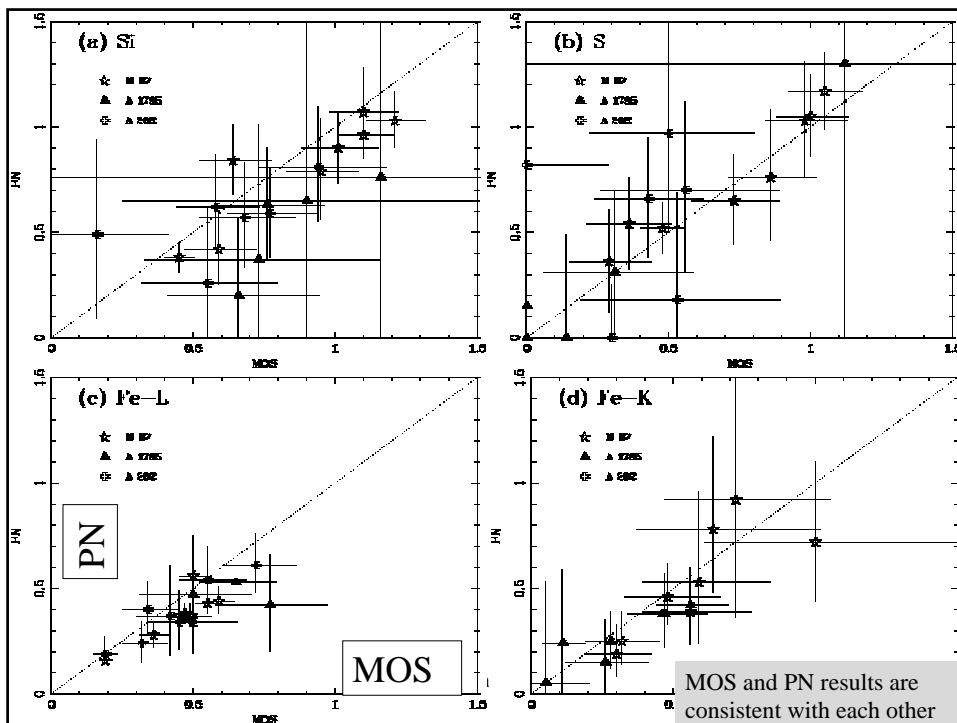
## Fitting

- ◆ Systematic errors:
  - ❖ Source 5-10 %
  - ❖ Background 10-35 %
- ◆ Collisional Ionization Equilibrium model (mekal).
- ◆ Fixed  $N_H$  (Galactic).
- ◆ A single temperature model, except for some central regions (2T model).
- ◆ Free parameters:
  - ❖ Norm, T, O, Ne, Mg, Si, S, Ar, Ca, and Fe abundances.

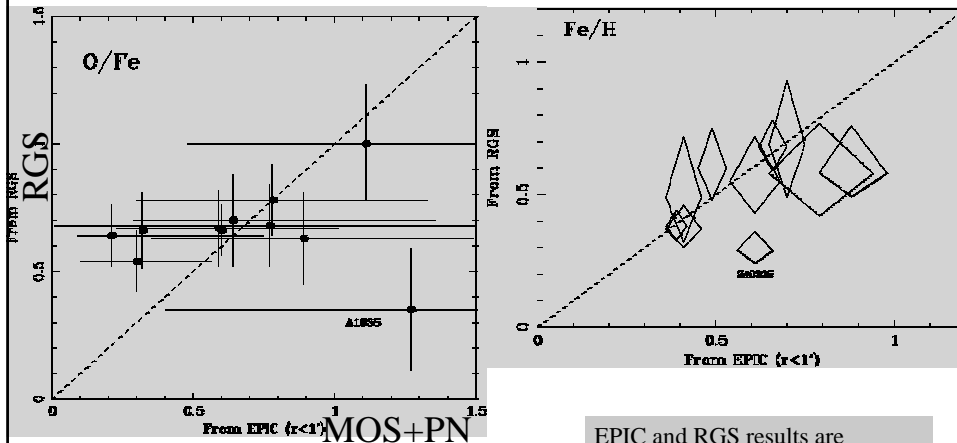
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# Calibration: EPIC vs. RGS



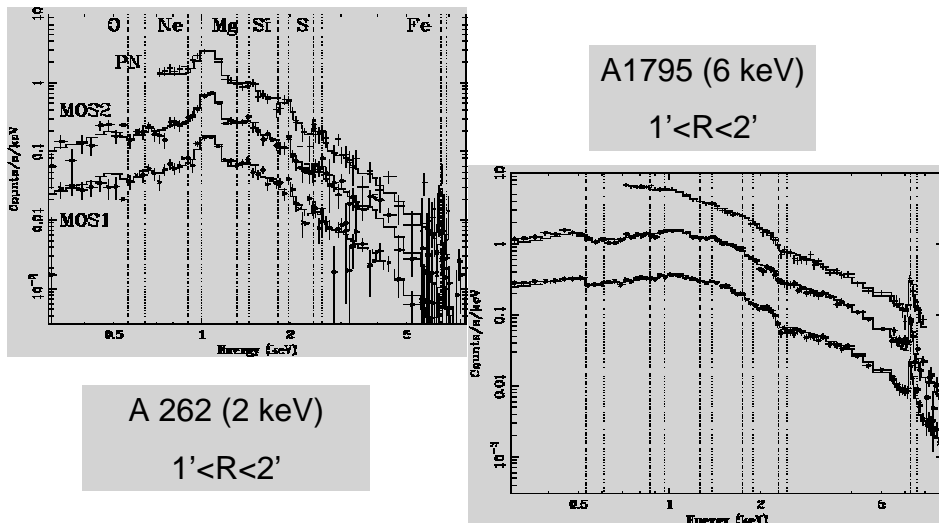
EPIC and RGS results are consistent with each other with some exception.

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# EPIC Spectra and best-fit models

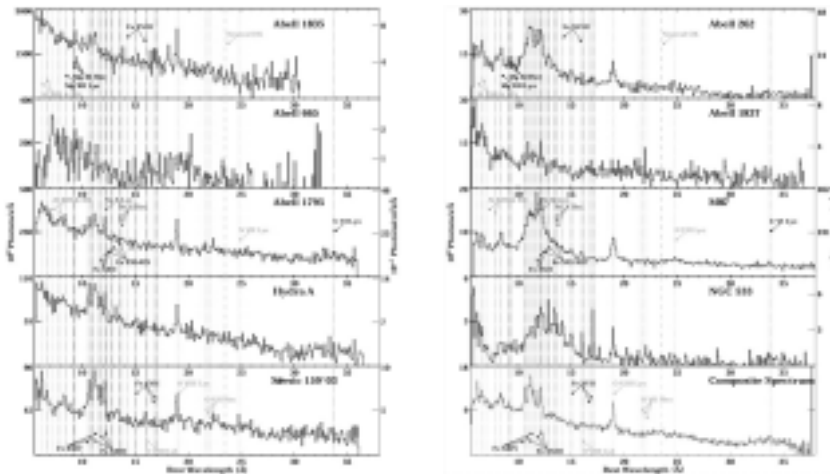


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# XMM/RGS spectroscopy of the cluster cores ( $r < 50$ -100 kpc)



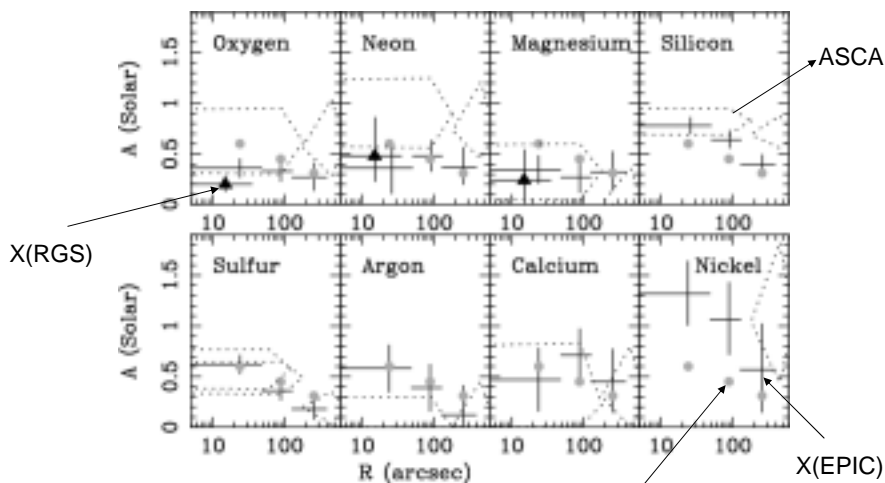
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(Peterson et al. 2003)

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## Best example (A496)

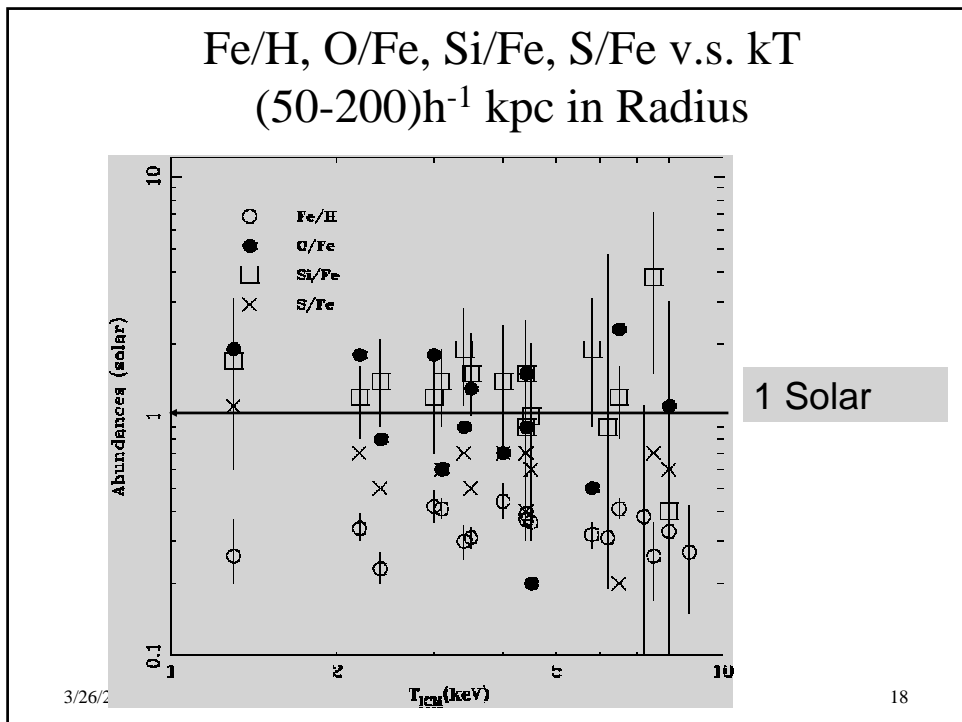
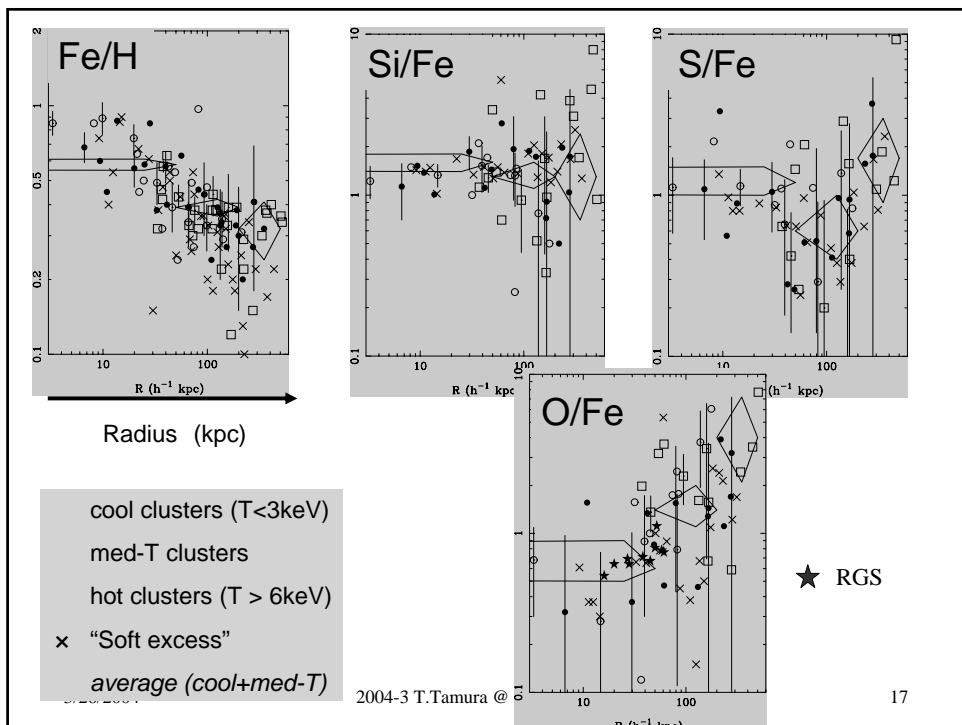


From Tamura et al. 2001

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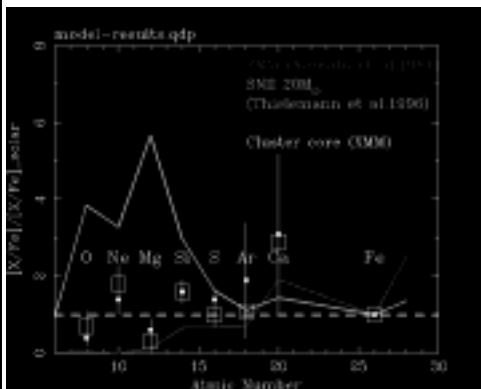




# Present Results

1. No significant variation in the Fe abundance and the Si, S, and O ratios to the Fe among the systems.
2. The O/H and O/Fe ratio in the cluster cores, are  $0.34 \pm 0.03$  and  $0.63 \pm 0.05$ , respectively. The r.m.s. deviation is comparable to the measurement errors on these ratios.
3. In all clusters with a temperature less than 6keV, except for MKW~9, we detected a central increase in the Fe abundance; 0.6-0.8 solar at the center, 0.2-0.4 solar in outer region.
4. The Si/Fe and S/Fe ratios in cool and medium temperature clusters are radially uniform within  $(200-500)h^{-1}kpc$  with mean values of  $1.4 \pm 0.2$  and  $1.1 \pm 0.3$ , respectively.
5. Contrary to the Fe, Si, and S abundances, the O abundance shows no spatial variations. When we combine the results from several clusters, we detected a significant radial variation in the O/Fe ratio.

## Discussion I: SN ratio in the cluster centers (accurate measure of O)



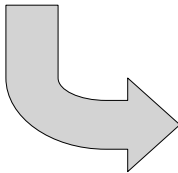
- ◆ The observed metal ratios (e.g., O/Fe) are between SNIa and SNII predictions.
- ◆ The cluster center gas could be produced by SNIa+SNII.
- ◆  $N_{Ia}/N_{II} \sim 0.6$ ,  
 $M_{Fe}^{Ia}/M_{Fe}^{total} \sim 0.8$ ,  
 $M_{O}^{Ia}/M_{O}^{total} \sim 0.05$

## Discussion II: total Oxygen mass and total number of SNIi at the cluster core

Measurement  
Observed O mass within  $50h^{-1}$   
kpc :  
 $10^8\text{--}2 \times 10^9 h^{-2.5} \text{ Msun}$

Theoretical assumption :

1. All O was originated from SNIi.
2. One SNIi produces 2 Msun Oxygen (Tsujimoto et al. 1995).



$10^8\text{--}2.5 \times 10^9$  of SNIi .  
 $10^7$  year (a typical life time of a  
20 Msun star)  $\times$  (10-200) SNIi  
/year.  
(cf. a typical starburst galaxy  $\sim$   
a few SNIi/year)

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## Discussion III: Origins of the ICM metals

- ◆ Si, S, Fe show similar central increase, but O shows no spatial variations.
- ◆ Consistent with that Si-S-Fe for a large part have a common origin, while the O has a different origin.
- ◆ One possibility:
  - ❖ Outer region (Cluster as a whole): Past SNIi and SNIa metal has been mixed.
  - ❖ Central region : recent SNIa metal causes an excess in Si-S-Fe.

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# Future Prospects

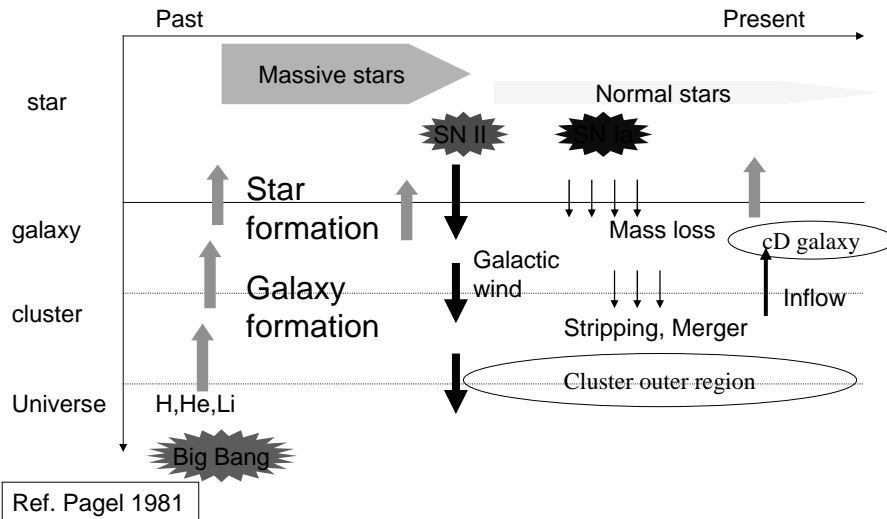
## Still large uncertainties in...

- ◆ O abundance in outer region of clusters.
  - ❖ Intrinsic EW of O lines is smaller than the CCD energy resolution.
  - ❖ Much cooler component (e.g. Soft excess/WHIM) could emit the O lines.
  - ❖ Astro-E2 XRS or XIS.
- ◆ Fe abundance in much outer region.
  - ❖ The X-ray brightness is low in outer region, but large amount of the ICM.
  - ❖ Line emission measurements is limited by background and telescope PSF tail and stray photons.
  - ❖ Line absorption of metals could be used in outer region in future. XMM/RGS
- ◆ Other elements such as C, N, Ne, Mg, Ni...
  - ❖ Detailed measurements in M87/XMM (e.g. Finoguenov et al. 2002).
  - ❖ Astro-E2 XRS.
- ◆ Redshift evolution of the metals.
  - ❖ We only know metallicity within  $z < 0.3-0.5$ . Metal productions may occurred at  $z > 2-3$ .
  - ❖ Next generation satellites.

## References

- Tamura et al. 2001, A&A 379, 107
- Peterson et al. 2003, ApJ, 590, 207
- Kaastra et al. 2004, A&A, 413, 415
- Tamura et al. (2004) A&A accepted

# Cosmic Chemical Evolution

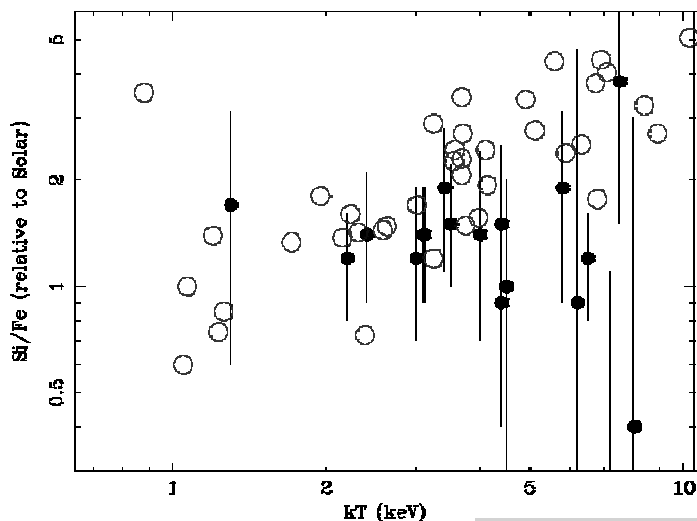


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## ASCA and XMM Results (Si/Fe)



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ASCA (Fukazawa et al. 1998)  
XMM; This work

# Metal productions in supernovae

\* Still large uncertainty in SN II model.

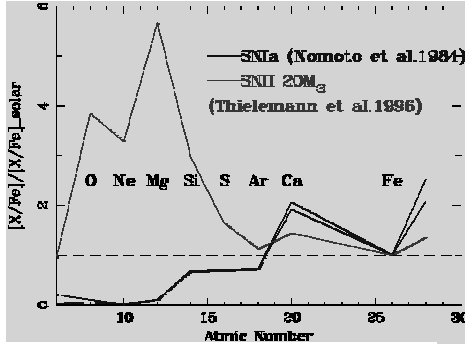
## SN Ia + II

SN Ia

3-8 Msun White dwarf.

N.S. driven by gas accretion from the companion.

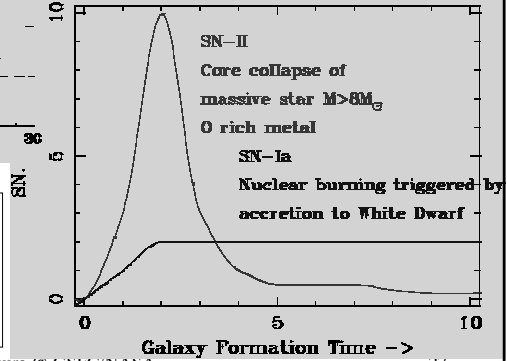
Ex. SN 1006



SN II

Massive stars ( $> 10$  Msun)  
Gravitational collapse

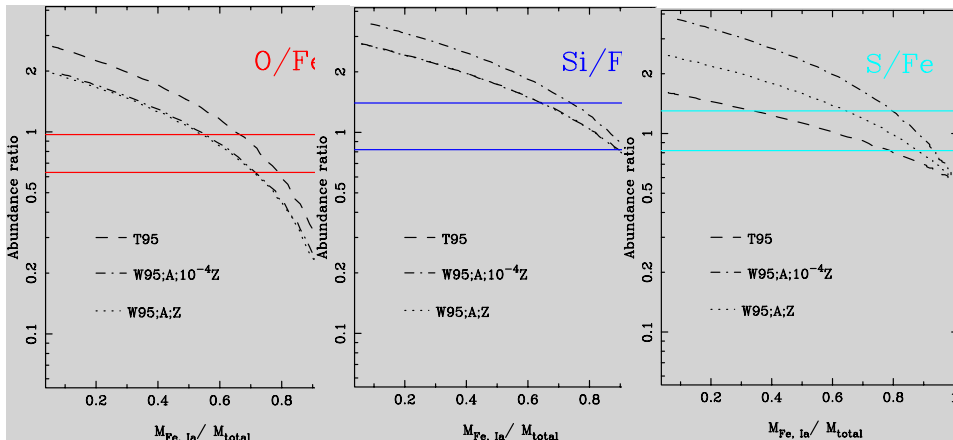
Ex. ) Cas-A



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